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Integration of biomass gasification with a Scandinavian mechanical pulp and paper mill – Consequences for mass and energy balances and global CO_2 emissions

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ABSTRACT

The Scandinavian mechanical pulp and paper industry has been facing great challenges during the past decades, mainly because of declining demand for newsprint, and higher prices on raw material and energy. One way of increasing profitability is to produce more value-added products besides the production of pulp and paper. In this study, integration potentials of three possible future biomass gasification-based energy mills with an existing thermo-mechanical pulp (TMP) mill, co-located with a sawmill, have been evaluated. The product gas was utilized for electricity production in a gas turbine, for production of methanol or for production of Fischer–Tropsch (FT) liquids. Integration of the energy mills showed good potential as the TMP mill constitutes a heat sink for which the excess heat from the energy mills can be utilized all year round. However, since there is little excess heat from the TMP mill at the required level to be utilized for biomass drying, for example, heat integration is typically one way. It has also been shown that integration of biomass gasification with a TMP mill results in larger CO_2 emissions reduction than stand-alone operation. Still, compared to co-firing biomass in a coal power plant, the energy mills all have lower potentials for CO_2 emissions reduction.

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1. Introduction

Due to declining demand for newsprint in Europe, the Scandinavian mechanical pulp and paper industry is experiencing difficulties with profitability. Therefore, the industry is now seeking options for creating more value-added products from the biomass, in addition to the production of pulp and paper. One promising alternative is gasification, which enables biomass to be converted into a gas rich in hydrogen and carbon monoxide. The gas can be synthesized into, for example transportation fuels or be burned in a gas turbine with high electrical efficiency. Integrating biomass gasification with existing mills for production of electricity and/or transportation fuels (hereafter referred to as “energy mills”) can technically be considered as a feasible alternative. Such process integration can potentially create important synergy effects. The hot gas stream from the gasifier, and from eventual consecutive synthesis units, can provide heat for the paper mill, thus replacing steam from the existing boiler. Part of the biomass feed input to the gasifier can also be provided by falling bark from the wood yard. Moreover, part of the required biomass to the energy mill can be provided locally if the mill is co-located with a sawmill, as approximately only half of the volumetric input to a sawmill ends up as sawn goods.

System aspects of gasification-based biorefinery concepts integrated with a pulp and paper mill have previously been examined by several authors. Most of these studies, however, focus on mills producing chemical pulp, thus mainly dealing with gasification of black liquor [1,2] but also gasification of wood fuel integrated with kraft mills [3–5]. Studies on biomass gasification in an integrated thermo-mechanical pulp and paper mill (TMP mill) have not been found in the open literature. In this paper, three possible processes for utilizing the gas produced via biomass gasification are evaluated using pinch analysis, i.e. combustion in a gas turbine for electricity production and production of two different transportation fuels, methanol and Fischer–Tropsch (FT) liquids.

Abbreviations: ASU, air separation unit; ATR, autothermal reformer; BF, background/foreground; CC, composite curve; CCS, carbon capture and storage; CFB, circulating fluidized bed; CHP, combined heat and power; FT, Fischer–Tropsch; GCC, grand composite curve; HLMPP, heat load model for pulp and paper; NGCC, natural gas combined cycle; TMP, thermo-mechanical pulp.

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The sizes of the different energy mills have been determined by the mill's required input of external heat, i.e. assuming that the energy mill replaces existing boilers. The different alternative biorefineries have been evaluated with respect to impact on the overall mill mass and energy balances and global emissions of CO_2, and are compared to the corresponding stand-alone facilities.

2. Pinch analysis

In this paper, possibilities for heat integration between the new process and the existing TMP plant have been evaluated using pinch analysis. Pinch analysis is a method with a structured approach which is used to design energy-efficient systems, i.e., to maximize internal heat recovery within a process (or between the processes to be integrated) and to minimize process demands for the hot and cold duties supplied by utilities. The grand composite curve (GCC) is used to identify the theoretical minimum net heat demand, or deficit, at a given temperature. Heat integration possibilities between two processes, for an idealized case, can be evaluated by combining the two GCCs into a so-called background foreground (BF) curve (for a description of the methodology, see for example Kemp [6] or Smith [7]).

3. Studied system: TMP and sawmills

The studied mill is a Scandinavian integrated TMP mill with an annual paper production of 930,000 tons and it is co-located with a large sawmill. Placing of a sawmill and a pulp mill in close proximity to each other is relatively common and is therefore of interest also in a general context. The layout of the TMP and the sawmills can be seen in Fig. 1. In total 98.6 MW_{LHV} (LHV = lower heating value, used exclusively throughout this paper) of bark from the debarking line at the TMP mill as well as bark, cutter shavings, sawdust and dried carvings[1] from the sawmill are available from the two mills. A stream of high-grade wood chips from the sawmill is replacing some pulp wood in the TMP lines (see Fig. 1).

The GCC for the mill studied in this paper is based on a simplified pinch analysis of the mill, performed earlier by using the HLMPP[2] tool [8,9]. The HLMPP tool provides a first quick scan of possibilities for efficiency measures in mechanical pulp and paper mills. Fig. 2 illustrates the GCC for the integrated TMP mill excluding the sawmill. The mill has a minimum hot utility demand of 130.5 MW of which 71.5 MW is provided through recovered steam from the refiners. A heat load of 40.2 MW, of the remaining 59 MW, has to be provided by low-pressure (LP) steam at 3.5 bar and 139 °C for technical reasons, and the remaining 18.8 MW at lower temperature levels (see Fig. 2).

The sawmill requires another 16 MW for its dryer, which is constructed to utilize hot water from 120 °C down to 95 °C. Since the mill's pinch temperature is at 72 °C, no heat integration is possible, i.e. this heat demand has to be covered with primary heat.

Altogether, this results in a total minimum primary heat demand for the site of 75 MW (59 MW for the TMP mill + 16 MW for the sawmill). This primary heat demand is satisfied by a steam boiler currently using 88.2 MW of the available biomass (assuming a boiler efficiency of 85%). The steam boiler produces high-pressure (HP) steam at 60 bar which is throttled down to just above the LP steam pressure (3.5 bar). A relatively simple measure for improvement would be to install a back-pressure turbine for electricity production, thus creating a combined heat and power (CHP) plant. Such a measure would result in an electricity production of 17.8 MW and an addition of 10.6 MW of biomass input. CHP operation will serve as the base case in this study.

The 75 MW heat deficit determines the sizes of the proposed energy mills studied in this paper. By utilizing excess heat from the energy mill in the TMP and the sawmills, the existing biomass boiler can be replaced. Heat loads associated with the mills are summarized in Table 1. In addition to heat demands, the TMP mill consumes 194 MW of electricity, mainly for the refiners.

There is an increasing trend to take out forest residues in connection with logging. At the moment, combined heat and power plants, based on conventional steam cycles, are the main purchasers but the material might as well be gasified. An investigation has shown that there is annually 1.55 TWh (182 MW) of tops, branches and stubs available within a 100 km radius from the site [10]. This quantity is assumed to be the first option of purchase if the biomass residues on site are insufficient to feed the gasifier, since round wood is assumed to be too valuable to be gasified.

4. Production and utilization of product gas

Production of transportation fuels and/or electricity through gasification generates large amounts of heat which would end up in the hot gases. This excess heat is often suggested to be used in a district heating system, but with the drawback of requiring less heat during the warmer part of the year. A paper mill, though, has a relatively constant heat demand regardless of season, thus potentially posing a heat sink for the syngas from the gasifier the whole year around.

The three different energy mill options studied are summarized in Fig. 3. Gasifier, tar cracker and initial gas cleaning are the common process units for all three processes. At this stage, the gas is considered clean enough to be combusted in a gas turbine [11].

For production of methanol and FT liquids, the methane as well as longer-chain hydrocarbons are reformed into syngas[3] which is then adjusted via the water-gas-shift reaction (reaction (1)) to reach the appropriate ratio of hydrogen to carbon monoxide. Synthesis of FT liquids, however, requires an additional cleaning step. The process layout is described in more detail below. The simulation software Aspen Plus [12] has been used to model all units, except drying, gasification and the gas turbine. The tar cracker has been modelled according to the principles described by Spath et al. [13], the gas cleaning, reformer, shift reactor and methanol synthesis according to Hamelinck and Faaij [14], the Rectisol unit (a commercial unit for acid gas removal) according to Larson et al. [15] and the FT synthesis according to Ekbom et al. [16].

Temperature and composition, given as mole-%, of the gas after each step are presented in Table 2. The steps are further described below.

4.1. Pretreatment and gasification

Biomass is transformed into raw gas through thermo-chemical conversion, i.e. gasification. The first step is usually chipping, before the biomass is dried, in order to avoid too much moisture in the syngas. It is assumed that the initial moisture content of the incoming biomass is 50 wt-% and that it is dried to 15 wt-%, with a specific heat demand of 2750 kJ/kg of evaporated moisture [11],

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[1] Carvings are created when the dried sawn goods are adjusted in order to meet the customers' specifications.

[2] Heat load model for pulp and paper [6].

[3] In this paper, synthesis gas (or syngas) is defined as a gas containing hydrogen, carbon monoxide, carbon dioxide and water as main constituents. Product gas is a combustible gas which contains methane and longer hydrocarbons, besides the components of the syngas. Raw gas is produced in the gasifier and is defined as a product gas with considerable amounts of tars.

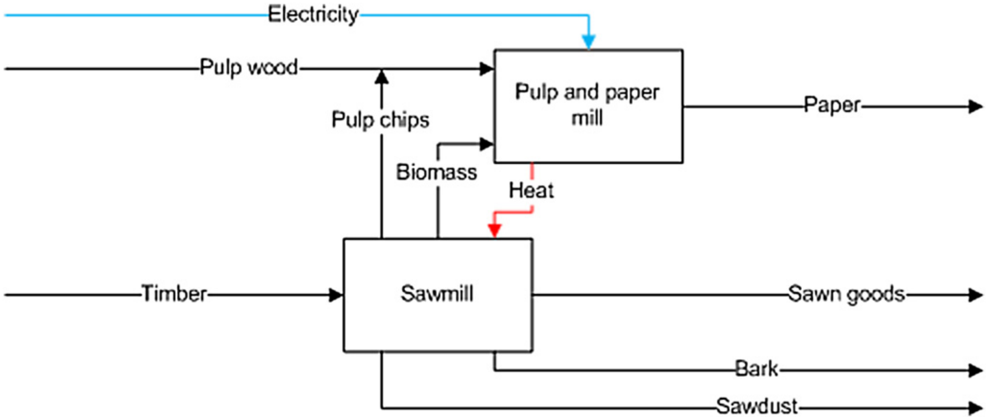

Fig. 1. Energy and material flows of the TMP mill and the sawmill, producing paper and sawn goods (electricity excluded). The biomass going from the sawmill to the pulp and paper mill consists of sawmill residues (bark, sawdust, cutter shavings), covering the demand of the steam boiler.

before entering the gasifier. Carvings from the sawmill are not assumed to require any further drying, though.

There are a number of different technologies for biomass gasification which can be characterized as fixed-bed, fluidized-bed and entrained-flow gasifiers. Oxygen-blown directly heated gasifiers or indirect gasifiers can be used to avoid contamination of nitrogen in the syngas. If a liquid fuel is the desired end-product, higher temperature in the gasifier produces a syngas with better quality (rich in hydrogen and carbon monoxide) that contains fewer hydrocarbons and tars: in practice an oxygen-blown entrained-flow gasifier which can be operated at up to 1300 °C. However, extensive milling and/or torrefaction or pyrolysis is required to be able to feed biomass into an entrained-flow gasifier. For combustion in a gas turbine, an air-blown, atmospheric, gasifier could in principle be used as long as the heating value would not drop significantly. Fluidized-bed gasifiers that operate at lower temperatures, around 800–900 °C, provide a gas with an acceptable tar content due to the homogeneous temperature distribution in the bed, and does not necessitate the extensive milling associated with entrained-flow gasification.

The gasifier in this study is a pressurized, oxygen- and steam-blown circulating fluidized-bed (CFB), operating at 25 bar and 850 °C and with specifications according to Hamelinck et al. [17]. Operation at elevated pressure and the use of oxygen instead of air as the oxidizing media allow smaller equipment downstream. Oxygen also has the advantage of not diluting the syngas with nitrogen, which is particularly important if downstream conversion to other products is targeted. Oxygen is produced by an on-site, cryogenic, air separation unit (ASU) with a specific electricity consumption of 300 kWh/ton of oxygen [17]. Production of liquid fuels takes place at elevated pressure and it is therefore an advantage to keep the gasification pressurized in order to avoid downstream compression of the syngas. However, the methanol synthesis is carried out at 90 bar, which is not a realistic operating pressure for a gasifier. Thus, further compression is necessary for that case.

4.2. Gas cleaning and conditioning

Cracking of tars and other hydrocarbons, formed during gasification of biomass, into carbon monoxide and hydrogen takes place in a catalytic tar cracker, designed according to Spath et al. [13]. The gas enters the cracker, which is a bubbling fluidized bed, at the gasification temperature (i.e. 850 °C) and leaves at around 670 °C.

In this study, wet gas cleaning, described by Hamelinck and Faaij [14], has been applied in all three cases to remove particulates and other impurities in the product gas. The particulates could poison the catalysts, used in methanol and FT synthesis, or cause corrosion in the gas turbine or heat exchangers. Solid particles are removed in a cyclone before the gas is cooled down to just above the dew point (a dew point of 170 °C is considered). Particulates and alkalis, which condense on particles, are removed in a bag filter before the gas passes through a wet scrubber, for final cleaning, where it is cooled down to 40 °C below the dew point.

Due to the relatively large methane content in the product gas, the gas has to be reformed prior to methanol or FT liquids synthesis. An oxygen-blown autothermal reformer (ATR) has therefore been selected for the reformation of methane, ethane and ethylene into carbon monoxide and hydrogen. Besides carbon monoxide and hydrogen, carbon dioxide and water are also formed by oxidizing part of the feed product gas in order to provide heat for the highly endothermic reforming reactions. This results in an outlet temperature of 1000 °C.

Finally, the hydrogen to carbon monoxide ratio is adjusted in an additional step to fit the subsequent synthesis by utilizing the water-gas-shift reaction according to:

$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad (1)$$

The reaction proceeds almost to completion at ~200 °C. The desired hydrogen to carbon monoxide ratio is defined by the downstream reaction and is met by by-passing the shift reactor with a sub-stream.

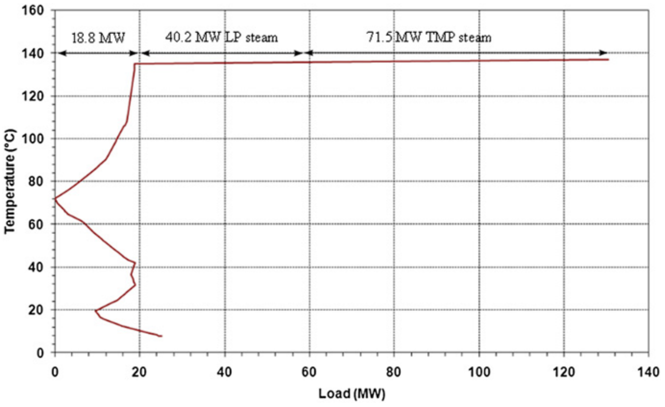

Fig. 2. GCC of the integrated TMP mill without the sawmill using the HLMPP tool.

Table 1
Hot utility demands of the TMP mill and the sawmill.

	Heat load [MW]
Steam demand covered with reformed steam	71.5
Steam demand covered with primary LP steam	40.2
Heat demand at lower temperature levels	18.8
Total TMP mill hot utility demand	130.5
Hot water demand of the sawmill	16
Total hot utility demand of the site	146.5
Total net hot utility demand of the site (reformer steam excluded)	75

Table 2
Gas composition, expressed as mole-%, and temperature after each consecutive process step of the energy mill.

	T [°C]	H_2	CO	CO_2	H_2O	CH_4	C_2H_4	C_6H_6	N_2	Tar
Gasifier[a]	850	15.0	10.8	23.5	36.9	12.4	0.5	0.2	0.6	0.1
Tar cracker	677	25.9	13.0	23.5	27.7	9.2	0.13	0.06	0.51	Trace
Wet gas cleaning	127	38.3	18.8	20	10.6	11.4	0.15	0.07	0.68	0
Reformer (ATR)	1 000	35.6	25.4	11.6	26.8	0.1	0	0	0.5	0
Water-gas-shift	200	38	18.1	15.9	27.4	0.1	0	0	0.5	0
Acid gas separation	−60	67	31.9	0.1	0	0.2	0	0	0.8	0

[a] The gasifier feed is in this case assumed to be hog fuel (bark, shavings, sawdust and other residues) with the following composition: ash 1.9 wt-% dry basis, C 49.9 wt-% dry ash-free (d.a.f.), H 6.11 wt-% d.a.f., O 42.9 wt-% d.a.f., N 0.62 wt-% d.a.f., and LHV = 15.89 MJ/kg (15 wt-% moisture).

4.3. Syngas utilization

As previously stated, three different processes for utilizing the produced product/synthesis gas have been evaluated in this study, i.e. electricity production in a combined cycle and production of two potential transportation fuels, methanol and FT liquids. Each of the processes is described in detail in this section.

4.3.1. Gas turbine

Production of electricity in a combined cycle can be seen as a relatively simple and robust option for utilizing the product gas. The gas is fed to the gas turbine after the gas cleaning step. Hot flue gases, from the gas turbine, at 583 °C, are used to generate HP steam for the steam cycle, and a back-pressure turbine expands the steam down to LP level for utilization in the mills. Flue gases down to 80 °C are used for drying of the incoming biomass. The required dryer heat load determines the temperature of the flue gases into the dryer, and thereby also how much of the heat in the flue gases can be used for production of HP steam.

4.3.2. Methanol synthesis

Methanol is one of the biggest bulk chemicals in the world, serving as raw material for plastics and paint, etc. Currently, the main feedstock is natural gas, and methanol from biomass could therefore serve as an attractive carbon-neutral replacement. Methanol has also been suggested as an additive to petrol, similar to how ethanol is used today, but with the benefits of having a larger biomass to fuel yield and a higher octane number. However, methanol has a rather poor energy density (726 kJ/mole for methanol compared to 1367 kJ/mole for ethanol [18]).

In the second proposed biorefinery process, the syngas is utilized for synthesis of methanol. Drying of the biomass is assumed to take place below the reaction temperature for the methanol synthesis, in order to be able to utilize excess heat from the methanol synthesis unit for drying. The product gas is required to be processed in an ATR followed by a water-gas-shift, in order to meet the desired synthesis conditions. Steam is added in the water-gas-shift reactor (reaction (1)) to shift the hydrogen to carbon monoxide ratio to 2:1 in order to maximize the yield. No acid gas removal is used in this case since the liquid-phase methanol process is insensitive to carbon dioxide [14]. The methanol synthesis reactions (reactions (2) and (3)) take place at 90 bar and 240 °C in the presence of Cu/Zn/Al as catalyst in a slurry bubble column. The conversion yield of carbon monoxide is assumed to be 75% for hydrogen to carbon monoxide ratios above 2. Unreacted syngas is recirculated to the reactor inlet with a recycle-to-feed ratio of maximum 2. The off-gas is assumed to be combusted in an existing steam boiler on site [14].

$$2H_2 + CO \leftrightarrow CH_3OH \tag{2}$$

$$3H_2 + CO_2 \leftrightarrow CH_3OH + H_2O \tag{3}$$

Separation and purification take place in two flashes and two distillation columns, reaching a purity of 99.7 wt-% for methanol.

4.3.3. FT synthesis

Fischer–Tropsch fuels, especially diesel, have received growing attention during the last years as they are directly usable in today's engines. FT diesel is also interesting as a hydrogen source via onboard reforming in cars since it does not contain any sulphur that can poison the fuel cell catalyst.

In the Fischer–Tropsch process, named after two German scientists, hydrogen and carbon monoxide react and form longer hydrocarbons according to reaction (4):

$$(2n+1)H_2 + nCO \rightarrow C_nH_{(2n+2)} + nH_2O \tag{4}$$

where n represents the length of the hydrocarbon. In the model used in this paper, the FT reaction has been considered analogous to a polymerization reaction following the Anderson–Schultz–Flory distribution, and is expressed by:

$$\frac{W_n}{n} = (1-\alpha)^2\alpha^{n-1} \tag{5}$$

where W is the weight fraction of molecules containing n carbons and α is the growth probability factor. A large α indicates large

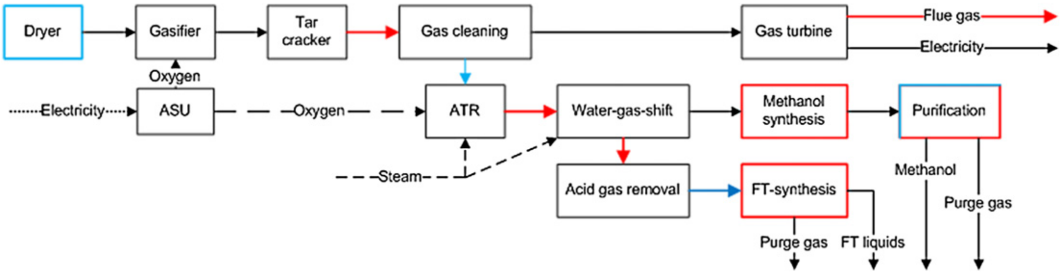

Fig. 3. Process layout for the three different energy mills. Red indicates a hot stream or process unit that needs to be cooled and blue indicates a cold stream that needs to be heated. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

probability for long carbon chains and vice versa. The reaction takes place at 23 bar and 210 °C and the carbon monoxide conversion is assumed to be 90% per pass.

The reaction occurs in a slurry-phase reactor (SPR) and is modelled according to Ekbom et al. [16], using a Co catalyst. The preceding synthesis steps, from biomass feed, reforming and gas cleaning, are the same as for the methanol production process. In order to avoid poisoning of the sensitive FT catalyst, virtually all sulphur (<1 ppm) has to be removed prior to the reactor [16]. Besides, the carbon dioxide has a negative influence on the C_{5+} selectivity [17]. To reach that level of purity a Rectisol-like unit is implemented to remove acid gases, such as hydrogen sulphide, carbonyl sulphide and carbon dioxide, using methanol as an absorbent. The design of the Rectisol-like unit has been simulated according to specifications in Larson et al. [15]. Drying of the biomass is, similarly to the methanol case, assumed to take place below the reaction temperature for FT synthesis. To maximize the FT liquids production, the unreacted gas is partly recycled back to the ATR in order to crack undesired methane and butane compounds that have been synthesized in the FT reactor. Carbon dioxide is removed in the acid gas removal unit before the gas enters the FT reactor. Off-gases are extracted to avoid accumulation of inert compounds and are combusted in an existing boiler.

Cracking of waxes, isomerization and further treatment into finished fuels are assumed to take place at an existing refinery, which is taken into account when the CO_2 emissions are calculated (see Section 5.5).

5. Heat integration possibilities

As can be seen in Fig. 2, excess heat is available at around 60 °C, which has been assumed to be at too low a temperature level and of too low quantity to be utilized directly for particular parts of the processes, e.g. drying. The opportunities for heat pumping have not been examined in this study.

A steam cycle has been selected to utilize the excess heat from the energy mills for production of electricity in a steam turbine, wherever large temperature differences exist between a hot stream and a cold stream, i.e. between the hot gas from the gasifier, or the flue gases from the gas turbine, and the TMP mill. Steam at 60 bar is produced in accordance with existing steam data, and is expanded down to 3.8 bar to allow a 0.3 bar pressure drop down to 3.5 bar, which is the LP steam level (see for example Fig. 4). Relatively low steam data was chosen in order not to run into corrosion problems caused by the reducing atmosphere in the product gas [19].

All evaluated biorefinery processes via gasification require a net import (see Table 3) of biomass to feed the gasifier. Forest residues with a moisture content of 50% and an LHV of 8.4 MJ/kg [20] are assumed to serve as an additional fuel input to the gasifier, since such biomass exists in vast amounts in the area around the mill.

5.1. Gas turbine

Fig. 4 shows the original mill's GCC together with the sawmill in blue and the GCC for the energy mill with a gas turbine as the upper red line, in a BF curve. The steam cycle is shown in between. HP steam is generated from high-grade heat and is expanded down to LP level as a way of utilizing the large temperature difference between the two processes. The arrows indicate transfer of heat from hot to cold stream.

An input of 220 MW of wet biomass is required in order for the energy mill with a gas turbine to cover the steam demand of the mill as suggested in Fig. 4, which means that 121.4 MW has to be imported in addition to the 98.6 MW that is available on site. The net electricity production of 83.5 MW, after 3.8 MW has been used for cryogenic separation of air, results in an electrical efficiency (ratio of electricity to wet biomass) of 38%, and covers around 43% of the mill's electricity demand.

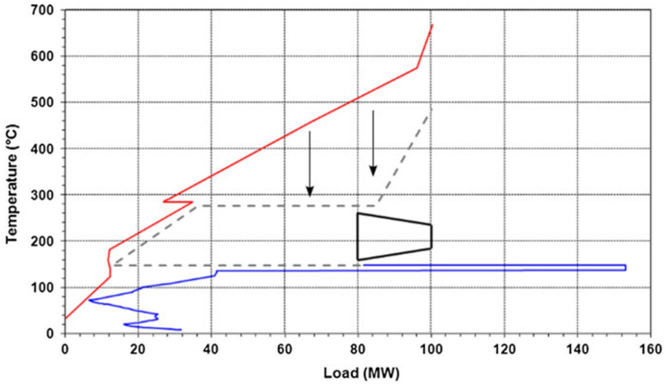

Fig. 4. GCC for the energy mill with a gas turbine (upper red line), the TMP mill and the sawmill (lower blue line) and the steam cycle (dashed line). Reformed TMP steam is represented by the additional line at LP level. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

5.2. Methanol

Fig. 5 shows the BF curve for the energy mill with methanol production in the foreground (red) and the TMP/sawmill in the background (blue). In addition, the steam cycle is shown.

Due to the high steam demand in drying and purification steps, the size of the methanol plant has to be fairly large in order to cover the steam demand of the mills. Significant amounts (28 MW) of off-gases are purged from the process, which are assumed to be combusted in an existing steam boiler at 85% efficiency. High-temperature syngas generates HP steam for electricity production and provides heat for the mill as well as the reboilers in the distillation columns. Altogether, off-gas and syngas heat included, 25.7 MW of electricity is produced. However, more than that, 40.1 MW, is used in the ASU, and for compressor work.

The methanol production adds up to around 322 MW (51% wet biomass to fuel efficiency). The wet biomass to fuel efficiency is 51%, which is similar to what is reported in the literature (50–57% in Ref. [14]).

Input load to the gasifier is 635 MW on a wet basis, which implies that 536.4 MW has to be imported, equivalent to more than seven truck loads per hour. Such large amounts of forest residues are not available within a reasonable distance from the site. Better integration with the mill is necessary to be able to scale down the energy mill.

One option for advanced integration would be to utilize excess heat from the mill to run the distillation reboiler in the methanol

Table 3
Summary of results for the energy mills, with and without the sawmill.

	Gas turbine		Methanol		FT liquids	
Sawmill [w/ or w/o]	w/	w/o	w/	w/o	w/	w/o
Biomass load [MW]	220	177	635	483	285	221
Biomass import [MW] [a]	121.4	141.7	536.4	447.7	186.4	185.7
Truck loads per day [b]	39	46	172	144	60	60
Electricity surplus/deficit [MW]	83.5	65.9	−14.4	−11.3	−18.6	−14.34
Fuel production [MW]	–	–	322	245	148	115

[a] The 98.6 MW available on site when co-located with a sawmill; else 35.3 MW of bark is available from the pulp mill wood yard.

[b] In addition to transportation of wood for paper and sawn goods. 32 tons of forest residues per truck [21].

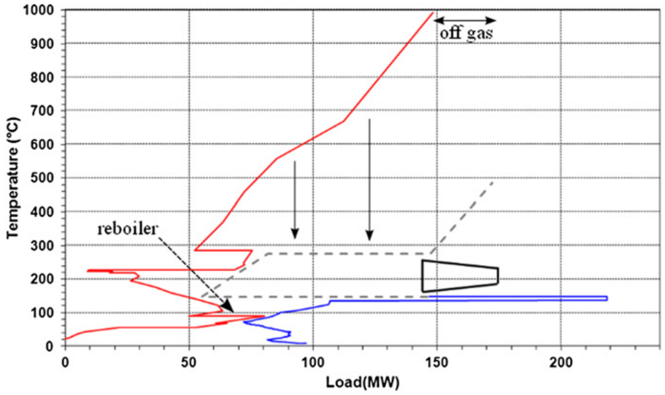

Fig. 5. GCC for the energy mill with methanol production (upper red line), the TMP mill and the sawmill (lower blue line) and the steam cycle (dashed line). Reformed TMP steam is represented by the additional line at LP level. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

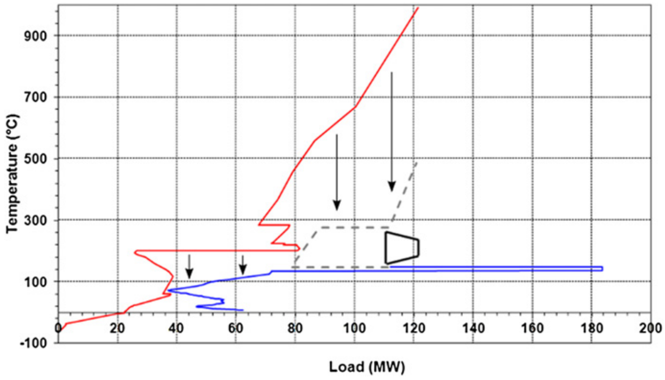

Fig. 6. GCC for the FT process (upper red line), the TMP mill and the sawmill (lower blue line) and the steam cycle (dashed line). Reformed TMP steam is represented by the additional line at LP level. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

synthesis process (highlighted in Fig. 5). In practice, that would be done by lowering the pressure in the distillation column and thereby also lowering the reboiler temperature. A column pressure down to 0.2 bar is realistic and would result in a temperature of 55 °C in the reboiler. However, utilization of excess heat below the pinch, mainly exhaust air from the paper machines, does not seem a realistic option due to the small temperature difference causing a relatively small overlap, and is therefore not further evaluated.

5.3. *FT liquids*

To cover the heat demand of the studied mill, the FT plant needs an input of at least 285 MW on a wet basis. This would, in turn, mean that 186.4 MW of the gasifier feed has to be imported. The FT liquids production on this scale is 148 MW, which results in a biomass to FT liquids efficiency of 52%. This is on the same order of magnitude as described for FT fuels in [3], where the efficiencies range from 46 to 62%, based on the LHV.

Fig. 6 shows the BF curve of the FT process (foreground, red) and the mill (background, blue), together with the steam cycle. HP steam is produced from the gases after the gasifier and reformer, and the back-pressure steam covers the heat demand in the process where LP steam is required. There is a possibility to utilize the 3 MW of off-gases generated in the FT process as well. However, existing boilers have higher minimum load and this option is therefore not considered here. The generated steam is expanded through a turbine down to 3.8 bar, producing 9.2 MW of electricity, which covers part of the electricity demands for the ASU and the Rectisol plant of 27.8 MW.

5.4. *Summary of heat integration study*

The following table summarizes the main results and figures from the three evaluated gasification processes: gas turbine, production of methanol and production of FT liquids. The results are presented with, as well as without, the saw mill. If the mill is assumed not to be co-located with the saw mill, the heat demand decreases by 16 MW. However, at the same time, the amount of biomass available on site decreases from 98.6 MW to 35.3 MW.

The additional transport should be compared with the current frequency of transportation of wood for production of sawn goods and paper which is around 130 trucks per day.

Table 4 shows the relative change in biomass usage and electricity/biofuel production for the mill integrated with the energy mills compared to the mill base case.

5.4.1. *Comparison with stand-alone facilities*

The three evaluated energy mills were compared with the performance of corresponding stand-alone facilities. The extra biomass used for the integrated cases, compared to the base case, is now instead fed to the stand-alone plant. Excess heat is utilized by generating electricity in a condensing steam turbine, instead of a back-pressure steam turbine, for these cases. Table 5 shows the resulting electricity surplus/deficit and biofuel production in the stand-alone plants.

5.5. *CO_2 emission balances*

The CO_2 emission balances for the mill integrated with the energy mills are evaluated in a life cycle perspective using system expansion. Net flows of energy and material entering or leaving the plant, for the mill integrated with the energy mills compared to the mill base case, are assumed to cause a change in the surrounding system. This is illustrated in Fig. 7.

A net surplus or deficit of electricity is assumed to affect the marginal electricity production. Since the timeframe for the gasification projects studied is relatively long, base load build margin rather than operating margin is considered. The base load build margin is here defined as the type of electricity generation grid capacity addition affected by implementation of the gasification project in question. It is assumed that the base load build margin production in the modelled time period will still occur in

Table 4
Summary of results for integrated cases including the sawmill. The fact that the availability of biomass exactly matches the demand for the base case is simply a coincidence.

	CHP	Gas turbine	Methanol	FT liquids
Biomass [MW_{LHV}]				
Demand	98.6	220	635	285
Available on site[a]	98.6	98.6	98.6	98.6
Surplus/deficit[b]	0	−121.4	−536.4	−186.4
Electricity [MW]				
TMP/sawmill	−194	−194	−194	−194
Energy mill	17.8	83	−14.4	−18.6
Surplus/deficit[c]	−176.2	−111	−208.4	−212.6
Compared to base case[d]	–	−65.2	32.2	36.4
Biofuel [MW_{LHV}]	–	–	322	148

[a] [Available on site – demand].
[b] [Surplus/deficit (base case) – surplus/deficit (energy mill)].
[c] [TMP/sawmill + energy mill].
[d] [Surplus/deficit (base case) – surplus/deficit (energy mill)].

Table 5
Summary of results for stand-alone cases.

	Gas turbine	Methanol	FT liquids
Biomass demand [MW_{LHV}]	121.4	536.4	186.4
Electricity surplus/deficit [MW]	53.0	−4.7	−0.4
Biofuel production [MW_{LHV}]	–	272	96.4

Table 6
Marginal electricity production technologies and related CO_2 emissions.

	Coal power	Coal power w. CCS	NGCC
CO_2 emissions [kg/MWh_{el}]	680	129	329

condensing power plants fired with fossil fuel [22]. Three state-of-the-art fossil electricity production technologies are considered as build margin technologies: coal power, coal power with CCS, and NGCC. The CO_2 emissions for these marginal electricity production technologies are presented in Table 6.

Methanol can replace petrol in conventional engines with only minor modification, and studies show that blending methanol in petrol has positive effects on the efficiency at certain ratios [23]. In this study, however, 1 MWh of methanol is assumed to replace 1 MWh of petrol. The life cycle emission of CO_2 from petrol is approximately 274 kg/MWh [24]. Distribution of methanol is assumed to cause CO_2 emissions of 4.0 kg/MWh_{fuel} [25].

The FT liquid is a semi-finished product and has to be upgraded in a refinery before usage. The CO_2 emissions reduction is assumed to be the amount of “green” CO_2 released during complete combustion of the FT liquid (i.e. the “green” carbon replaces fossil carbon), which equals 255 kg/MWh. Upgrading to transportation fuels in a conventional refinery and distribution, both of feedstock and of motor fuel, are assumed to cause about the same amount of emissions regardless of feedstock. As described in Section 4.3.3, CO_2 is removed as part of the process in the FT liquid case. If an infrastructure for CCS is established near the mill, this relatively pure stream of CO_2 (23. tonnes/h) could be compressed and sent for storage.

As can be seen in Table 4, all energy mills need substantial amounts of external biomass. As has been stated, there is 182 MW available within a 100 km radius from the mill. This is enough to satisfy the demand for the electricity case and almost the entire demand for the FT case. However, for the methanol case, a larger collection area is required. It has been assumed that the available biomass per unit area is the same outside the 100 km radius as inside it. Given that a truck on average needs 35 litres of diesel per 100 km, the CO_2 emissions over the same distance are 93 kg. The annual demand for raw material of the mill sets the required logging area (assumed to be circular for simplicity), which in turn sets the average transportation distance, i.e. the distance to cover half of the logging area (times two to account for the return journey). This approach has been applied both for the integrated cases and for the stand-alone cases. Logging of forest residues results in 3.4 kg of CO_2 per harvested MWh [26].

There is a possibility that the demand for biomass on the European market will grow to an extent where it will become a limited resource in the midterm future, i.e. it is not possible to solve the whole climate problem by substituting biomass for fossil fuels. Under these conditions, the extra biomass used at the mill when integration with the energy mills is considered, compared to the mill base case, could decrease the amount of biomass available for other applications. Therefore, it is important to compare the CO_2 effect of the integration of the different energy mills not just in relation to each other, but also in relation to other possible large biomass users. Another potential large biomass user is a coal power plant, co-firing biomass. The resulting net savings of CO_2 emissions, for coal substitution, are 336 $kg/MWh_{biomass}$.

5.5.1. Results and discussion

Fig. 8 shows the CO_2 emissions reduction for the three evaluated cases, divided by the necessary extra biomass input compared to base case operation, considering the three marginal electricity production technologies presented in Table 6.

Which of the three energy mills gives the highest CO_2 emissions reduction is dependent on the marginal electricity production technology. The gas turbine case with its large electricity surplus, compared with the mill base case, benefits from a high-CO_2-emitting marginal electricity production technology (coal or NGCC). The biofuel cases, methanol and FT liquids, on the other hand, with their electricity deficits, compared with the mill base case, benefit from a low-CO_2-emitting marginal electricity production technology (coal with CCS). If transportation fuel is the preferred end-product, methanol shows the greatest potential for a single mill. However, since the FT case gives the largest specific reduction, several FT

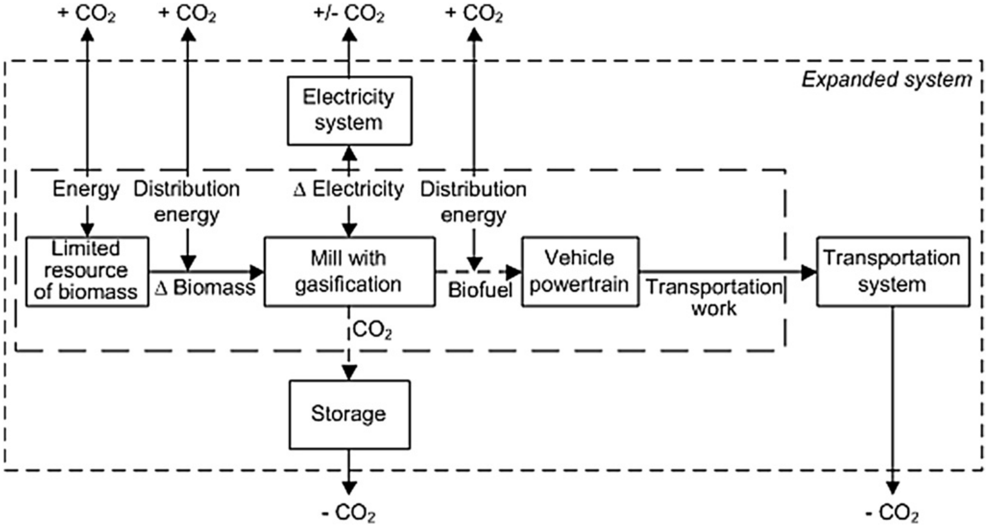

Fig. 7. A schematic representation of net flows entering or leaving the mill and how they interact with the surrounding system. The CO_2 effect of each flow is indicated with +/±, where + means an increase and − means a decrease in CO_2 emissions.

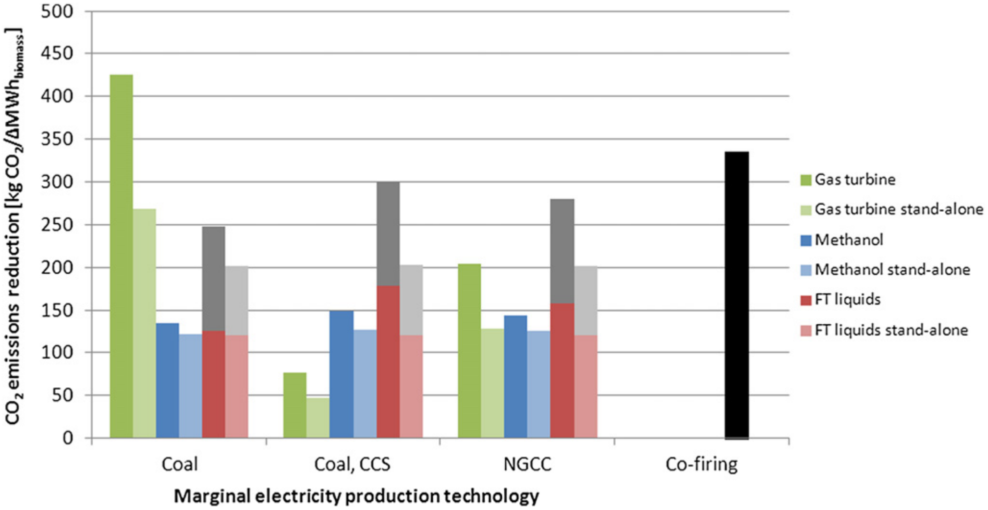

Figure 8. Specific CO_2 emissions reduction of integrated and stand-alone energy mills, and the CHP plant, considering the three marginal electricity production technologies presented in Table 6. The grey bar, on top of a red bar, indicates the reduction potential if the separated CO_2 from the FT process is captured and stored. The specific CO_2 emissions reduction of co-firing biomass in a coal power plant is also shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

plants, located at different mills, would give the largest overall reduction. The reason for FT to have the largest specific reduction is dependent on the smaller plant size, compared to methanol. The amount of available biomass on site is fixed, while the amount of external biomass depends on the size of the energy mill. The specific reduction is calculated as the produced amount of transportation fuel per unit of external biomass input.

Even though large quantities of biomass are being transported in some cases, that contribution has only a marginal impact on the overall emissions and does not affect the results. This is also why the impact of not being co-located with a sawmill is not shown here, since the only difference is the contribution from extra transportation.

The evaluated integrated cases are compared with the corresponding stand-alone cases. As shown in Fig. 8, the integrated options always give the highest CO_2 emissions reduction, no matter what would be the future electricity build margin technology.

As an additional comparison, the specific emissions from co-firing biomass in a coal power plant are shown to the right (in black) in Fig. 8. As can be seen in the figure, the gas turbine case is the only case that can beat co-firing of biomass in a coal power plant when comparing potential CO_2 emissions reduction. Both of the biofuel cases always have a significantly lower CO_2 reduction potential than co-firing with coal. Thus, the biofuel cases do not have the highest CO_2 emissions reduction potential in any of the scenarios presented below if compared with both the gas turbine energy mill and co-firing with coal. In a midterm future when the demand for biomass probably exceeds the supply, usage of biomass in one plant results in less biomass being available for other plants/technologies. At that time it could be questionable, from a climatic point of view, to use biomass for biofuel production. However, as shown in Fig. 8, if it is possible to store the CO_2 separated from the FT process (grey bars), the CO_2 emissions reduction potential for that process is close to the one for co-firing with coal if coal with CCS, or NGCC, constitutes the marginal electricity production technology. The methanol process presented in this article does not enable capture of CO_2 in the same way as for the FT since there is no CO_2 separation prior to the synthesis. Whether or not the power plant in which co-firing takes place is equipped with CCS does not affect the results. This implies that storage of CO_2 from biomass is seen as a negative emission.

Fig. 9 shows the absolute annual potential for CO_2 emissions reduction for the three evaluated energy mills. A methanol plant

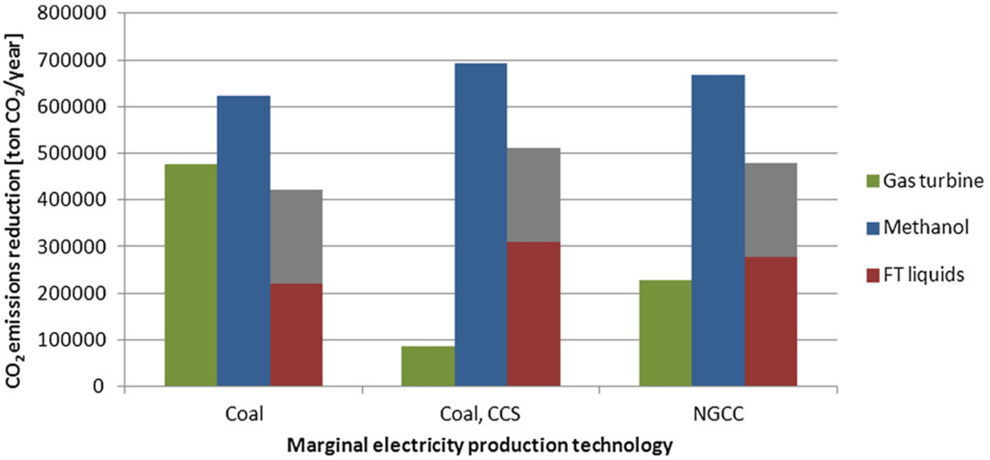

Fig. 9. Absolute CO_2 emissions reduction for the three evaluated integrated energy mills and the CHP plant. The grey bar, on top of a red bar, indicates the reduction potential if the separated CO_2 from the FT process is captured and stored. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

with the proposed configuration can be built at a larger scale than the other options, if the size is determined by the steam consumption of the mill, and the CO_2 emissions reduction is therefore larger for methanol in such a comparison.

6. Conclusions

In this paper, integration potentials of three biomass gasification-based energy mills with an existing TMP mill, co-located with a sawmill, have been evaluated. The product gas has been utilized for electricity production in a gas turbine, production of methanol or production of FT liquids. Integration of the energy mills was found to show good potential as the TMP mill constitutes a heat sink for which the excess heat from the energy mills can be utilized all year round. In a typical integrated TMP mill there is no excess heat at the required level to be utilized for biomass drying, for example. The heat integration is therefore typically one way, i.e. from the energy mill to the pulp and paper mill and the sawmill. Wherever there is a large enough temperature difference between the process streams, the heat integration is accomplished through the use of a steam cycle, for all three energy mills.

Among the three studied energy mills, the gas turbine case requires the smallest gasifier size, when sized to cover the heat demand of the mill. The gas turbine case was also found to be the alternative which requires a biomass input that does not exceed the availability of forest residues in the mill region (100 km radius).

The FT plant requires a larger biomass input than the gas turbine case, thus requiring a larger logging district or the use of higher-grade wood. Due to the shape of the GCC, utilization of excess heat in a steam cycle is quite limited, compared to the other two cases.

The energy mill with methanol production requires by far the largest supply of biomass if the size-determining requirement is to fully replace existing steam boilers with excess heat from the energy mill. A more than twofold increase of the truck transportations through the mill would most likely pose some logistical challenges. A more comprehensive technical and economic analysis is necessary to be able to identify the best gasification route for this particular mill.

Which of the energy mills shows the largest potential for global CO_2 emissions reduction is dependent on the marginal electricity production technology. In the case of a coal power plant or NGCC, the gas turbine case gives the highest reduction of CO_2 emissions per unit of biomass input, while in the case of coal power with CCS the biofuel cases, especially the FT case, give the highest reduction of CO_2 emissions per unit of biomass input. It has also been shown that integration of biomass gasification with a TMP mill results in larger CO_2 emissions reduction than stand-alone operation. Compared to co-firing biomass in a coal power plant, the energy mills all have lower potentials for CO_2 emissions reduction. However, if it is possible to store separated CO_2 in the FT case, this case could contribute to nearly as large CO_2 emissions reduction as co-firing biomass in a coal power plant.

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